REPORT DOCUMENTATION PAGE		Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
09-07-2015	Final Report	10-Jun-2012 - 9-Jun-2015

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Final Report: Intrinsic Information Processing and Energy Dissipation in Stochastic Input-Output Dynamical Systems	W911NF-12-1-0234
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
	611102

6. AUTHORS	5d. PROJECT NUMBER
James P Crutchfield	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES	8. PERFORMING ORGANIZATION REPORT NUMBER
University of California - Davis 1850 Research Park Drive Suite 300 Davis, CA 95618 -6153	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	ARO
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)
	61757-EG.19

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

Recent theoretical and experimental advances in nonequilibrium thermodynamics provide a new understanding of how "intelligent" control can convert information to energy. However, these approaches have yet to account for the diverse kinds of information that complex nonlinear systems are capable of producing and storing. This is particularly a concern regarding the diversity of differently structured irreversible processes, which play key role in limiting computation. Fortunately, computational mechanics accounts for this diversity, but in autonomous dynamical systems. Thermodynamic cycles that perform useful information processing are nonautonomous

15. SUBJECT TERMS
input-output processes, controlled thermodynamics systems, nonlinear dynamics, chaos, nonequilibrium, symbolic dynamics, dissipation, information processing

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE	UU		James Crutchfield
UU	UU	UU			19b. TELEPHONE NUMBER
					530-752-0060

Report Title

Final Report: Intrinsic Information Processing and Energy Dissipation in Stochastic Input-Output Dynamical Systems

ABSTRACT

Recent theoretical and experimental advances in nonequilibrium thermodynamics provide a new understanding of how "intelligent" control can convert information to energy. However, these approaches have yet to account for the diverse kinds of information that complex nonlinear systems are capable of producing and storing. This is particularly a concern regarding the diversity of differently structured irreversible processes, which play key role in limiting computation. Fortunately, computational mechanics accounts for this diversity, but in autonomous dynamical systems. Thermodynamic cycles that perform useful information processing are nonautonomous systems. To analyze information processing in nonautonomous systems, computational mechanics must be ex- tended to controlled dynamical systems. Additionally, it must be augmented to account for the energetics that support information generation and storage.

The project's goal was to synthesize the new nonequilibrium thermodynamics and computational mechanics into a single framework. The project successfully reached this goal and, leveraging that success, the research effort continues under the ARO-based MURI "Information Engines" (W911NF-13-1-0390), under the PI's leadership. The framework now provides techniques to analyze and predict the mechanisms by which energy flows support information processing. Using these, we are developing broadly applicable principles of emergent organization and hierarchy in complex physical and biological systems, including new bounds on the minimum required energy dissipation.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
07/08/2015	4.00	Ryan G. James, John R. Mahoney, Christopher J. Ellison, James P. Crutchfield. Many roads to synchrony: Natural time scales and their algorithms, Physical Review E, (04 2014): 42135. doi: 10.1103/PhysRevE.89.042135
07/08/2015	15.00	D. P. Varn, P. M. Riechers, J. P. Crutchfield. Pairwise correlations in layered close-packed structures, Acta Crystallographica, (06 2015): 423. doi: 10.1107/S2053273315005264
07/08/2015	14.00	Christopher C. Strelioff, James P. Crutchfield. Bayesian structural inference for hidden processes, Physical Review E, (04 2014): 42119. doi: 10.1103/PhysRevE.89.042119
08/27/2014	6.00	Sarah Marzen, James Crutchfield. Information Anatomy of Stochastic Equilibria, Entropy, (08 2014): 0. doi: 10.3390/e16094713
08/27/2014	7.00	Virgil Griffith, Edwin Chong, Ryan James, Christopher Ellison, James Crutchfield. Intersection Information Based on Common Randomness, Entropy, (04 2014): 0. doi: 10.3390/e16041985

TOTAL: **5**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received   Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

James P. Crutchfield, "Lecture Course on Information in Complex Systems", Complex Systems Summer School, Santa Fe Institute, Santa Fe, NM, 13 June 2013.

James P. Crutchfield, "Lecture Course on Intrinsic Computation", Complex Systems Summer School, Santa Fe Institute, Santa Fe, NM, 14 June 2013.

James P. Crutchfield, "Computation at the Nanoscale: Thoughts on information processing in novel materials, molecules, & atoms", Telluride Summer Workshop on The Complexity of Dynamics & Kinetics in Many Dimensions, Telluride, Colorado, 16 June 2013.

James P. Crutchfield, "Exact Complexity: The Spectral Decomposition of Intrinsic Computation", Workshop on Information in Dynamical Systems & Complex Systems, Burlington, Vermont 18-19 July 2013.

James P. Crutchfield, "The Past and the Future in the Present", Berkeley Mini-Statistical Mechanics Meeting, UC Berkeley, 14 January 2013.

James P. Crutchfield, "The Macroscope: An Engine for Pattern Discovery", AstroInformatics, http://astroinformatics2012.org, Microsoft Research, Redmond, WA, 10-13 September 2012.

James P. Crutchfield, "Information Dynamics: Evolutionary Innovation, Children's Games, and Iterated Learning", Workshop on Information Theory and Game Theory, Santa Fe Institute, 13-16 August 2013.

Sarah Marzen (UCB), "Predictive Inference in Nonequilibrium Steady States", July 2014, Annual Meeting of the Society of Industrial and Applied Mathematics, Chicago, Illinois.

Sarah Marzen (UCB), "Information Theoretic Methods of Time Series Analysis", March 2014, Machine Learning seminar, Computer Science Department, University of Hawaii, Manoa.

Sarah Marzen (UCB), "Causal Structure of Neural Spikes Trains", April 2014, Redwood Center for Theoretical Neuroscience, UC Berkeley.

Sarah Marzen (UCB), "Causal Structure of Neural Spikes Trains", April 2014, Joint Redwood-Ganguli-Theunissen Lab Meeting, UC Berkeley.

Sarah Marzen, Mike DeWeese, Jim Crutchfield (UCD/UCB), "Statistical Complexity of Neural Spike Trains", Poster presentation, March 2014, Computational and Systems Neuroscience (Cosyne 2014), Salt Lake City, Utah.

Chris Hillar, Sarah Marzen, Urs Koster, and Killian Kopsal (UCD/UCB), "Hopfield Networks Efficiently Encode Images", Poster presentation, March 2014, Computational and Systems Neuroscience (Cosyne 2014), Salt Lake City, Utah.

Alec Boyd (UCD), "Demon Design", July 2014, Annual Meeting of the Society of Industrial and Applied Mathematics, Chicago, Illinois.

Korana Burke (UCD), "Chaos in Ryberg Atoms", 13-18 July 2014, Summer School on Shortcuts to Adiabaticity, Optimal Quantum Control, and Thermodynamics, Telluride Science Research Center, Telluride, Colorado.

Jim Crutchfield (UCD) taught two graduate courses Winter and Spring quarters 2014 on the physics of information and the physics of computation, respectively.

Jim Crutchfield (UCD) gave the John von Neumann Complexity and Computation Public Lecture "Demonology: The Curious Role of Intelligence in Physics & Biology", 6 November 2013, Wisconsin Institutes for Discovery, University of Wisconsin, Madison, WI.

Nix Barnett (UCD), "e-Transducers: Parts I, II, and III", 27 May and 9 and 16 July 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Alec Boyd and Greg Wimsatt (UCD), "Quantum Logic", 23 July 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Alexandra Nilles (UCD), "Applying Predicted Information Gain to Physically Embodied Agents", 13 August 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis; 14 August 2014, REU Presentations, Physics, UC Davis.

Benny Brown (UCD), reviewed Little and Sommer "Learning and exploration in action- perception loops", 21 May and 18 June 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Alec Boyd (UCD), review of Mlodinow and Brun, "Relation between the psychological and thermodynamic arrows of time"", 14 May 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Sarah Marzen (UCB), "Information Anatomy of Continuous Stochastic Processes", 16 April 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Alec Boyd and Paul Riechers (UCD), reviewed of Gavin Crooks' UC Berkeley nonequilibrium discussion group "Holes" presentation, 9 April 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Ryan James (U Colorado, Boulder), "Intersection Information", 2 April 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Alec Boyd (UCD), reviewed Klages et al Chapter 4 "Measuring Out of Equilibrium Fluctuations", 26 February 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Korana Burke and Greg Wimsatt (UCD), reviewed PRL "Measurement of Stochastic Entropy Product", 12 March 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Alec Boyd (CD), reviewed Kawaguchi et al "Fluctuation theorem for hidden entropy production", 19 February 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Pooneh Mohammadiara (UCD), "Elusive Information", 5 February 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Sarah Marzen (UCB), "Structural Complexity of Stochastic Renewal Processes", 29 January 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Alec Boyd (UCD), reviewed Klages et al Ch. 1 "Fluctuation Relations", 11 and 18 December 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

J. P. Crutchfield (UCD), "Information in Infinitary Processes", 3 December 2013, Workshop on Information in Infinitary Processes, 3-4

December 2013, Complexity Sciences Center, UC Davis.

Sarah Marzen (UCB), "Continuous-Time Processes", 3 December 2013, Workshop on Information in Infinitary Processes, 3-4 December 2013, Complexity Sciences Center, UC Davis.

Chris Strelioff (UCD), "Inferring Infinite-State Processes", 3 December 2013, Workshop on Information in Infinitary Processes", 3-4 December 2013, Complexity Sciences Center, UC Davis.

lec Boyd (UCD), "Information Engines", 3 December 2013, Workshop on Information in Infinitary Processes, 3-4 December 2013, Complexity Sciences Center, UC Davis.

Paul Riechers (UCD), "Spectral Decomposition", 3 December 2013, Workshop on Information in Infinitary Processes, 3-4 December 2013, Complexity Sciences Center, UC Davis.

Korana Burke (UCD), reviewed PRE "Information Content in Turbulence", 20 November 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

J. P. Crutchfield (UCD), "Information in Infinitary Processes", 13 November 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

J. P. Crutchfield (UCD), reviewed "Learning in embodied action-perception loops through exploration", 30 October 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Dowman Varn (UCD), "MultiAgent Dynamical Systems", 23 October 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Korana Burke (UCD), reviewed Milnor and Thurston's "Kneading Calculus", 25 September and 2 and 9 October 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Alec Boyd (UCD), "Information Engines: Parts I and II", 21 and 28 August 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Brenden Roberts (UCD), "Study of Time Reversal in Physical Processes", 14 August 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Number of Presentations: 48.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

<u>Received</u>   <u>Paper</u>

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

<u>Received</u>   <u>Paper</u>

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper

07/08/2015 13.00 Nicholas F. Travers, James P. Crutchfield. Equivalence of History and Generator Epsilon-Machines,
arxiv.org:1111.4500 [math.PR] (12 2011)

07/08/2015 18.00 Dibyendu Mandal, James P. Crutchfield, Alexander B. Boyd. Identifying Functional Thermodynamics in Autonomous Maxwellian Ratchets,
PHYSICAL REVIEW X (06 2015)

07/08/2015 17.00 Alexander B. Boyd, James P. Crutchfield. Demon Dynamics: Deterministic Chaos, the Szilard Map, and the Intelligence of Thermodynamic Systems,
Physical Review Letters (submitted) (06 2015)

07/08/2015 16.00 J. P. Crutchfield, N. Barnett. Computational Mechanics of Input-Output Processes: {Structured} transformations and the epsilon-transducer,
Journal of Statistical Physics (12 2014)

08/27/2014 5.00 Ryan G. James, Korana Burke, James P. Crutchfield. Chaos forgets and remembers: Measuring information creation, destruction, and storage,
Physics Letters A (06 2014)

08/27/2014 10.00 James P. Crutchfield, Christopher J. Ellison, Paul M. Riechers. Exact Complexity: The Spectral Decomposition of Intrinsic Computation,
arxiv.org:1309.3792 [cond-mat.stat-mech] (09 2013)

08/27/2014 8.00 Christopher C. Strelioff, James P. Crutchfield. Bayesian structural inference for hidden processes,
Physical Review E (04 2014)

08/30/2013 1.00 Nicholas F. Travers, James P. Crutchfield. Equivalence of History and Generator epsilon-Machines,
J. of Theoretical Probability (08 2013)

08/30/2013 2.00 James P. Crutchfield, Christopher J. Ellison. The Past and the Future in the Present,
Physical Review E (10 2012)

08/30/2013 3.00 Ryan G. James, John R. Mahoney, Christopher J. Ellison, James P. Crutchfield. Many Roads to Synchrony: Natural Time Scales and Their Algorithms,
Physical Review E (02 2013)

TOTAL: **10**

Number of Manuscripts:

Books

Received   Book

  TOTAL:

Received   Book Chapter

  TOTAL:

Patents Submitted

Patents Awarded

Awards

PI Crutchfield awarded two-year accelerated promotion due to research accomplishments supported by this grant.

PI Crutchfield's publication "Regularities Unseen, Randomness Observed" was selected by American Institute of Physics journal Chaos---A Journal of Nonlinear Science" as one of the top 10 publications in the journal's 25 year history.

Kevin Taylor, "Extending Reinforcement Learning Methods with a Simple Robot", Undergraduate Senior Thesis (June 2013), awarded Highest Honors by Physics Department.

Korana Burke: Assumed UC Davis Chancellor Postdoctoral Fellowship, Complexity Sciences Center, Physics Department (September 2012).

PI Crutchfield's publication "Chaos Forgets and Remembers" was highlighted in Nature:
P.-M. BINDER & R. M. PIPES, "How chaos forgets and remembers", Nature 510 (June 2015) 343-344.

PI Crutchfield's publication "Chaotic Crystallography" was hightlighted in Nature Materials:
P. Ball, "Beyond the Crystal", Nature Materials 13 (2014) 1003.

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Alexander Boyd	0.40	
Paul Riechers	0.40	
Cina Aghamohammadi	0.30	
Nix Barnett	1.00	
Sarah Marzen	0.00	
FTE Equivalent:	**2.10**	
Total Number:	**5**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Ryan G. James	0.40
Dowman P. Varn	0.30
FTE Equivalent:	**0.70**
Total Number:	**2**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
James P Crutchfield	0.25	
FTE Equivalent:	**0.25**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Brenden Roberts	0.00	Physics
Greg Wimsatt	0.30	Physics
Alexandra Nilles	0.00	Physics
FTE Equivalent:	**0.30**	
Total Number:	**3**	

Student Metrics
This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 3.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 3.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 3.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 3.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 1.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 3.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME
Ryan G. James
Christopher J. Ellison
Nicholas Travers
Total Number: **3**

Names of other research staff

NAME	PERCENT_SUPPORTED
Jordan van Aalsberg	0.30
FTE Equivalent:	**0.30**
Total Number:	**1**

Sub Contractors (DD882)

Inventions (DD882)

Final Progress Report - Contract # W911NF-12-1-0234
Proposal # 61757EG

(Reporting Period: July 2012 – June 2015)

Intrinsic Information Processing and Energy Dissipation in
Stochastic Input-Output Dynamical Systems

James P. Crutchfield, Principal Investigator
Complexity Sciences Center, Department of Physics
University of California, Davis, California 95616

Statement of the Problem Studied

Recent theoretical and experimental advances in nonequilibrium thermodynamics provide a new understanding of how "intelligent" control can guide the flow of disorganized thermal energy to useful work energy. However, these approaches have yet to account for the diverse kinds of information that complex nonlinear systems are capable of producing and storing. This is particularly a concern regarding the diversity of differently structured irreversible processes, that play key role in limiting computation. Fortunately, computational mechanics accounts for this diversity, but in autonomous dynamical systems. Thermodynamic cycles that perform useful information processing, in contrast, are nonautonomous systems. To analyze embedded information processing, computational mechanics must be extended to controlled dynamical systems. Additionally, it must be augmented to account for the energetics that support information generation and storage.

The project's goal was to explore the mathematical and theoretical foundations necessary to synthesize the new nonequilibrium thermodynamics and computational mechanics into a single framework. The project successfully reached this goal and, leveraging that success, the research effort continues under the ARO-based MURI "Information Engines" (W911NF-13-1-0390), under the PI's leadership. The framework now provides techniques to analyze and predict the mechanisms by which energy flows support information processing. Using these, we are developing broadly applicable principles of emergent organization and hierarchy in complex physical and biological systems, including new bounds on the minimum required energy dissipation for different kinds of information processing.

ApproachThe scientific approaches involved consist of:
--- Nonlinear complex dynamical systems: Gives a detailed and structural view of the state-space mechanisms in nonlinear systems that guide and constrain system behavior.
--- Nonequilibrium statistical physics and thermodynamics: Delineates the kinds of work and work cycles required to overcome irreversible processes.
--- Computational mechanics: Allows for the exact characterization of the intrinsic information processing in complex systems.

Several technical approaches will be used identify relevant structures in nonlinear complex systems—equilibria, limit cycles, invariant submanifolds, ε-machines, and measures of intrinsic computation. The approaches include:
--- Analytical methods to solve in closed-form for the simplest prototype system behaviors and emergent properties.
--- Symbolic computing to extend the range of closed-form analysis to nontrivial complex behaviors.
--- Large-scale simulation using high-performance computing to go beyond their limitations.
Typically, nonlinear systems admit analytical solutions only in special cases. HPC-based simulations allow one to explore physically realistic behaviors outside of analytically approximated regimes.

Relevance to Army
Success in these tasks will enhance a number of Army capabilities, including:
--- Fundamental science of nonequilibrium thermodynamics: This is key to understanding emergent organization in a wide range of mechanical, electronic, chemical, biological, and social processes of interest to the Army.
--- Fundamental science of physical information processing: We are developing methods to analyze the nonlinear dynamical mechanisms that underlie the coupling between energy and information flows in complex physical systems.
--- Minimum energy requirements: By setting new bounds on energy dissipation required for information processing, the results will allow for more accurate estimates of optimal energy efficiencies in a wide range of information processing and control systems of interest to the Army.
--- Design efficiency: Building on these bounds, the results will lead to new design paradigms for large-scale, complex systems of interest to the Army.

Summary of the Most Important Results

The original proposal's research strategy was to synthesize the three scientific areas via the following tasks.

--- Task A: Energetics Introduce energetics into computational mechanics' informational view of complex systems.

--- Task B: Input-Output Dynamical Systems Develop a symbolic dynamics appropriate to con- trolled (input-output) dynamical systems by extending computational mechanics from signal generators (ε-machines) to signal transducers (ε-transducers).

--- Task C: Efficiency of Thermodynamic Information Processing Cycles Perform detailed computational mechanics informational analysis of the cyclic process by which thermodynamic transformations convert control information to free energy.

vTask D: Microdynamics Perform a detailed dynamical systems analysis of the state-space or- ganization of the dynamics underlying this same cyclic process.

Though the original proposal was rather ambitious, we believe that each of the tasks was addressed. We also now know that there is much follow-up research to do. In particular, while Tasks A-C are being pursued via the follow-on "Information Engines" MURI, Task D seems particularly deserving future attention.

The Publications (P#), manuscripts Under Review (UR#), and Manuscript in Preparation (IP#) document the task accomplishments and scientific progress. Their publication data and associated reprints and preprints have been uploaded to https://extranet.aro.army.mil. They are listed again below in the Bibliography to provide references for the narrative summary of the accomplishments.

The main highlights for scientific progress and accomplishments over the project are:

--- Information control of thermodynamical systems: The project achieved its most important scientific goal to describe how two processes interact: the mathematical foundations of ε-transducers. In short, we successfully extended the computational mechanics of ε-machines to optimal minimal transducers (P8). This opens up a huge range of applications. For example, we now have the mathematical tools with which to analyze controlled nonlinear dynamical systems—what the original proposal called input-output dynamical systems. Another example is that we can exactly identify the informational contributions to the flow of information between two systems (IP3). A third, and perhaps the most concrete application, is to analyzing the informational properties of controlled thermodynamic transformations. We recast Szilard's Engine, a version of Maxwell's Demon, showing that (i) it is a chaotic dynamical system whose degree of instability determines its rate of converting thermal fluctuations to useful work (UR4). We also introduced a broad family of fully analyzable information ratchets that operate as engines, consuming random bits on a tape and using the information to guide converting thermal fluctuations to lift a weight against gravity (UR5).

--- Exact Complexity: A new level of analytical precision for all uses of information-theoretic measures of complexity was developed. All known complexity measures for stationary discrete-valued hidden processes and dynamical systems with generating partitions can now be calculated in closed form from their ε-machine, if the latter is finite. This has been critical to progress in a number of applications to calculating correlation functions, power spectral densities, and a wide range of information measures. We adapted and substantially extended the methods of holomorphic functional calculus to give closed-form expressions for all functions of ε-machine transitions matrices. The result is that quantities, previously analytically uncomputable, and those that required exponential computational resources are now given by exact, closed-form expression. In computational complexity terms, what were exponential complexity computations are now constant-time algorithms. This is a major advance in the computational efficiency of analyzing intrinsic computation in complex systems. It also gives much theoretical insight into the very nature of intrinsic computation. (UR3 and IP2)

Mixed-States as Efficient Representations: A key part of these advances was our extending the underlying representation, the so-called mixed states, beyond simple discrete-alphabet and symbolic-dynamic processes to vector-valued and high-dimensional dynamical systems. One practical consequence is that the computational efficiencies we now enjoy for analyzing the intrinsic computation in low-dimensional systems applies to arbitrarily high-dimensional systems, including spatially extended dynamical systems and dynamical networks. (IP4)

--- Information Processing in Multi-input, Multi-output Channels: We introduced a consistent set of measures of redundant, synergistic, and unique information in multi-input, multi-output channels. This gives a systematic way of decomposing shared or mutual information into unique "atomic" components and opens up a way to understand how state-space structures in nonlinear dynamical systems support distinct kinds of information processing. (P4)

Chaos Forgets and Remembers: This project's most historically surprising result showed how chaotic systems create, destroy, and store information. For over a half century chaotic dynamical systems were characterized by a single "system invariant", the rate at which they generated information, called the Kolmogorov-Sinai entropy rate. We showed that this rate consists of two radically distinct kinds of information processing: (i) a component that is created and dissipation and (ii) a component that is created but actively stored by the system. (P2, P3, and P9)

--- The foundational and insightful aspect of these results were acknowledged in a Nature News and Views commentary on (P2): P. M. Binder and R. M. Pipes, "How Chaos Forgets and Remembers", Nature 510 (19 June 2014) 343-344.

--- Intrinsic Computation in Continuous Systems: Computational mechanics has been successfully extended to processes over continuous-time and continuous-state. Our first results showed how to calculate the information anatomy of continuous-state

random walks in nonlinear potentials (P3). The second results showed how to do this for continuous-time memoryful renewal processes—a well known class of processes that is widely used, from statistical mechanics to geophysics and neuroscience (P9). For example, using these results, we analyzed the effect of time coarse-graining on information measures of complexity (IP1). To illustrate those mathematical methods, as an application we analyzed the statistical complexity and other intrinsic computation measures for neural spike trains (P6).
Synchronization: A key property of controlling nonlinear dynamical systems is how the driven system becomes correlated, or not, to the imposed driving signal. To understand this and frame it information-theoretically, we analyzed in some detail and then provided exact calculational algorithms to determine the amount and kind of information and time required for an observer to synchronize to a structured process. (P1)

--- Structural Inference: We developed a complete Bayesian inference method to infer the structure of hidden processes from time series data. This goes substantially beyond statistical parameter estimation methods typical of modern machine learning to estimation and modeling in that it makes minimal assumptions about the model classes. The latter, it should be emphasized, is the key issue when attempting to discover structure and not merely verify a structural modeling assumption. That is, our methods determine the appropriate model class from data directly. (P5)

--- Nonergodic Processes: We successfully extended the computational mechanics of ε-machines from describing the structure and intrinsic computation in stationary, ergodic processes to that in nonergodic processes. This opens up a much wider range of applications of computational mechanics to, for example, analyzing structural properties of ergodic decompositions, change-point processes, multi-arm bandit processes, and nonequilibrium steady states. (IP5)
Correlations in Finitary Processes: We showed how to calculate, exactly and in closed-form, the pairwise correlations for any stochastic processes generated by finite-state hidden Markov models. This extends our previous methods that required unifilarity of the generator to the general, unrestricted case of nonunifilar generators. To give a concrete application and physical meaning to the results we demonstrated how the methods provide new insights into the organization of chaotic one-dimensional crystals; that is, into those that have any degree of disorder. (P7)

--- Computational Mechanics Foundations: Several technical papers established critical and oft-assumed properties in computational mechanics. This first showed that the original "equivalence-class" or "history" definition of optimal, minimal unifilar predictors is equivalent to the "generator" definition (UR1). The second showed when it is possible, in working with information measures over semi-infinite pasts and semi-infinite futures, to replace them with ε-machine forward-time and reverse-time causal states. (UR2)

♀Bibliography

Resulting Journal Publications During Reporting Period
P1. R. G. James, J. R. Mahoney, C. J. Ellison, and J. P. Crutchfield, "Many Roads to Synchrony: Natural Time Scales and Their Algorithms", Physical Review E 89 (2014) 042135.
P2. R. G. James, K. Burke, and J. P. Crutchfield, "Chaos Forgets and Remembers: Measuring Information Creation, Destruction, and Storage", Physics Letters A 378 (2014) 2124-2127.
P3. S. Marzen and J. P. Crutchfield, "Information Anatomy of Stochastic Equilibria", Entropy 16 (2014) 4713-4748.
P4. V. Griffith, E. K. P. Chong, R. G. James, C. J. Ellison, J. P. Crutchfield, "Intersection Information based on Common Randomness", Entropy 16 (2014) 1985-2000.
P5. C. C. Strelioff and J. P. Crutchfield, "Bayesian Structural Inference for Hidden Processes", Physical Review E 89 (2014) 042119.
P6. S. Marzen, M. R. DeWeese, and J. P. Crutchfield, "Statistical Complexity of Neural Spike Trains", Computational and Systems Neuroscience (Cosyne), Abstract (2014) 1-2.
P7. P. M. Riechers, D. P. Varn, and J. P. Crutchfield, "Pairwise Correlations in Layered Close-Packed Structures", Acta Crystallographica Section A: Foundations and Advances 71:4 (2015) 423-443.
P8. N. Barnett and J. P. Crutchfield, "Computational Mechanics of Input-Output Processes: Structured transformations and the ε-transducer", Entropy (2015) to appear.
P9. S. Marzen and J. P. Crutchfield, "Informational and Causal Architecture of Discrete-Time Renewal Processes", Entropy (2015) to appear.

Manuscripts under Review and Technical Reports
UR1. N. F. Travers and J. P. Crutchfield, "Equivalence of History and Generator ε-Machines", Electronic Journal of Probability, resubmitted (2015). arXiv:1111.4500 [math.PR].
UR2. J. P. Crutchfield and C. J. Ellison, "The Past and the Future in the Present", Advances in Complex Systems (2015) submitted. arXiv:1012.0356 [nlin.CD].
UR3. J. P. Crutchfield, C. J. Ellison, and P. M. Riechers, "Exact Complexity: The Spectral Decomposition of Intrinsic Computation", Physics Letters A (2015) submitted. Santa Fe Institute Working Paper 13-09-028; arXiv:1309.3792 [cond-mat. stat-mech].
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Manuscripts in Preparation
IP1. S. Marzen and J. P. Crutchfield, "Time Resolution Dependence of Continuous-Time Information Measures", arxiv.org and Physics Letters A, submission expected November 2015.
IP2. P. Riechers and J. P. Crutchfield, "Spectral Decomposition of Structural Complexity", arxiv.org and Journal of Statistical Physics, submission expected October 2014.
IP3. N. Barnett and J. P. Crutchfield, "Computational Mechanics of Input-Output Processes:
Shannon Information Measures and Decompositions", arxiv.org and J. Statistical Physics, submission expected September 2015.
IP4. C. J. Ellison and J. P. Crutchfield, "On States of States of Uncertainty: Observer-Process Synchronization", arXiv.org and Journal of Statistical Physics, submission expected November 2015.
IP5. J. P. Crutchfield and C. J. Ellison, "Way More Than the Sum of Their Parts: From Statistical to Structural Mixtures", arXiv.org and Physical Review Letters, submission expected August 2015.
♀
Appendices

The bulk of the following information has been uploaded to the webforms at https://extranet.aro.army.mil. However, the following provides more detail.

Collaborations and Technology Transfer

Continued development of open source library "Computational Mechanics in Python" (CMPy) that consists of all of the project's constructive mathematical results and methods. Planned release as open source software package slated for Winter 2016.

This project led to the PI being awarded a ARO-based MURI. The expanded effort greatly broadens the impact of the current project's results in collaborations with other universities and via interactions with ARO and ARL (e.g., in Albuquerque, NM).

Ph.D. Degrees Earned During Reporting Period

--- Ryan G. James (Physics) completed Ph.D. August 2013.
--- Nicholas F. Travers (Mathematics) completed Ph.D. June 2013.
--- Virgil Griffith (Neuroscience, CalTech), Ph.D. Fall 2014.
--- Richard Watson (Mathematics) completed Ph.D. December 2014.

Postdoctoral Researchers Involved During Reporting Period

--- Korana Burke: (Physics) September 2012-2014.
--- Ryan G. James (Physics) completed Ph.D. August 2013.
--- John R. Mahoney (Physics) January 2015-present.
--- Dowman P. Varn (Physics) August 2014-present.

Graduate Students Involved During Reporting Period

--- Jason (Nix) Barnett (Mathematics) Ph.D. Fall 2015, expected.
--- Sarah Marzen (Physics, UCB) Ph.D. Fall 2016, expected.
--- Paul M. Riechers (Physics) Ph.D. Winter 2016, expected.
--- Alec Boyd (Physics) Ph.D. Spring 2016, expected.
--- Pooneh Mohammediari (Physics), M.S. Fall 2015, expected.
--- Benny Brown (Physics), M.S. Spring 2016, expected.
--- Greg Wimsatt (Physics) Ph.D. Spring 2016, expected.

Undergraduate Students Involved During Reporting Period

--- Alexandra Nilles (NSF REU undergraduate intern, Physics, 2014).
--- Greg Wimsatt (Undergraduate intern, Physics, 2013).
--- Kevin Taylor (Undergraduate intern, Physics, 2012-2013).
--- Brenden Roberts (NSF REU undergraduate intern, Physics, 2013).

Awards, Honors, and Appointments

--- PI Crutchfield awarded two-year accelerated promotion due to research accomplishments supported by this grant.
--- PI Crutchfield's publication "Regularities Unseen, Randomness Observed" was selected by American Institute of Physics journal Chaos—Journal of Nonlinear Science as one of the top 10 publications in the journal's 25 year history.
--- Kevin Taylor, "Extending Reinforcement Learning Methods with a Simple Robot", Undergraduate Senior Thesis (June 2013), awarded Highest Honors by Physics Department.
--- PI Crutchfield's publication "Chaos Forgets and Remembers" highlighted in Nature: P.-M. Binder and R. M. Pipes, "How chaos forgets and remembers", Nature 510 (June 2015) 343-344.
--- PI Crutchfield's publication "Chaotic Crystallography" highlighted in Nature Materials: P. Ball, "Beyond the Crystal", Nature Materials 13 (2014) 1003.
--- Ryan G. James: Assumed post-doctoral research position in Computer Science Department, University of Colorado, Boulder (September 2013-August 2014).
--- Ryan G. James: Assumed post-doctoral research position in Complexity Sciences Center, Physics, University of California, Davis (September 2014-present).
--- Nicholas F. Travers: Assumed post-doctoral research position in Mathematics Department, Technion University, Israel (September 2013-August 2015).
--- Nicholas F. Travers: Assistant Professor, Mathematics Department, University of Indiana, Bloomington. (September 2015-).
--- Korana Burke: UC Davis Chancellor Postdoctoral Fellowship, Complexity Sciences Center, Physics Department (2012-2014).
--- John Mahoney, Assumed post-doctoral research position in Complexity Sciences Center, Physics, University of California, Davis (September 2014-August 2017).
--- Sarah Marzen (Physics, UCB) UC Berkeley Chancellor's Graduate Fellow (Fall 2013-present).
vSarah Marzen (Physics, UCB) National Science Foundation Graduate Fellow (Fall 2013-present).

Additional information on programs, students, and faculty of the Complexity Sciences Center is available online: http://csc.ucdavis.edu/.

Talks and Presentations: For those by group members see Presentations section filed at https://extranet.aro.army.mil.

Sarah Marzen (UCB) "Computational Mechanics Review", July 2014, Hess Group at Columbia University.
Sarah Marzen (UCB) "Predictive Inference in Nonequilibrium Steady States", July 2014, Annual Meeting of the Society of Industrial and Applied Mathematics, Chicago, Illinois.
Sarah Marzen (UCB) "Information Theoretic Methods of Time Series Analysis", March 2014, Machine Learning seminar, Computer Science Department, University of Hawaii, Manoa.
Sarah Marzen (UCB), "Causal Structure of Neural Spikes Trains", April 2014, Redwood Center for Theoretical Neuroscience, UC Berkeley.
Sarah Marzen, "Causal Structure of Neural Spikes Trains", April 2014, Joint Redwood-Ganguli-Theunissen Lab Meeting, UC Berkeley.
Sarah Marzen, Mike DeWeese, Jim Crutchfield, "Statistical Complexity of Neural Spike Trains", Poster presentation, March 2014, Computational and Systems Neuroscience (Cosyne 2014), Salt Lake City, Utah.
Chris Hillar, Sarah Marzen, Urs Koster, and Killian Kopsal, "Hopfield Networks Efficiently Encode Images", Poster presentation, March 2014, Computational and Systems Neuroscience (Cosyne 2014), Salt Lake City, Utah.
Alec Boyd (UCD), "Demon Design" (UCD July 2014, Annual Meeting of the Society of Industrial and Applied Mathematics, Chicago, Illinois.
Korana Burke (UCD), "Chaos in Ryberg Atoms", July 2014, Summer School on Nonequilibrium Thermodynamics at the Molecular Scale, Telluride Science Research Center, Telluride, Colorado.
Training: JPC taught two graduate courses Winter and Spring 2014 on the physics of information and the physics of computation, respectively.
PI Crutchfield gave John von Neumann Complexity and Computation Public Lecture "Demonology: The Curious Role of Intelligence in Physics & Biology", Wisconsin Institutes for Discovery. (6 November 2013.)
Nix Barnett, "ε-Transducers: Parts I, II, and III", 27 May and 9 and 16 July 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
Alec Boyd and Greg Wimsatt, "Quantum Logic", 23 July 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
Alexandra Nilles, "Applying Predicted Information Gain to Physically Embodied Agents", 13 August 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis; 14 August 2014, REU Presentations, Physics, UC Davis.
Nick Travers (Technion), "Inversions and Longest Increasing Subsequence for k-Card-Minimum Random Permutations", 20 August 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
Aleksander Zujev "Coupled Systems", 25 June 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
Benny Brown, review of D. Little and F. Sommer "Learning and exploration in action-perception loops", 21 May and 18 June

2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Fritz Sommer (Redwood Ctr, UCB), "Predictive Information Gain for Adaptive Learning", 11 June 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Alec Boyd, review of Mlodinow and Brun, "Relation between the psychological and thermodynamic arrows of time", 14 May 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Amanda Young, "Quantum Spin Chains", 30 April and 7 May 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Sarah Marzen, "Information Anatomy of Continuous Stochastic Processes", 16 April 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Alec Boyd and Paul Riechers, review of G. Crooks' UC Berkeley nonequilibrium discussion group "Holes" presentation, 9 April 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Ryan James (U Colorado, Boulder), "Intersection Information", 2 April 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Alec Boyd, review of Klages et al Ch. 4 "Measuring Out of Equilibrium Fluctuations", 26 February 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Korana Burke and Greg Wimsatt, review of Physical Review Letter "Measurement of Stochastic Entropy Product", 12 March 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Alec Boyd, review's Kawaguchi et al "Fluctuation theorem for hidden entropy production", 19 February 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Katie Amrine (Dept Viticulture and Enology) on "Measuring 'Functional' Information in transfer-RNAs to detect and resolve inconsistencies in deep roots of the Tree of Life", 12 February 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Pooneh Mohammadiara on "Elusive Information", 5 February 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Sarah Marzen on "Structural Complexity of Stochastic Renewal Processes", 29 January 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

J. P. Crutchfield led discussion on research job prospects and planning scientific and academic careers, 22 January 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

J.P . Crutchfield led debriefing of Information Engine Kickoff Meeting and discussion of alternative experimental platforms, 15 January 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Alec Boyd, review of Klages et al Ch. 1 "Fluctuation Relations", 11 and 18 December 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

J. P. Crutchfield, "Information in Infinitary Processes", 3 December 2013, Workshop on "Information in Infinitary Processes", 3-4 December 2013, Complexity Sciences Center, UC Davis.

Dave Feldman (College of the Atlantic), "2D Information Theory", 3 December 2013, Workshop on "Information in Infinitary Processes", 3-4 December 2013, Complexity Sciences Center, UC Davis.

Chris Ellison (WID, Wisconsin), "Countably Infinite Processes", 3 December 2013, Workshop on "Information in Infinitary Processes", 3-4 December 2013, Complexity Sciences Center, UC Davis.

Sarah Marzen (UCB), "Continuous-Time Processes", 3 December 2013, Workshop on "Information in Infinitary Processes", 3-4 December 2013, Complexity Sciences Center, UC Davis.

Chris Strelioff, "Inferring Infinite-State Processes", 3 December 2013, Workshop on "Information in Infinitary Processes", 3-4 December 2013, Complexity Sciences Center, UC Davis.

Alec Boyd, "Information Engines", 3 December 2013, Workshop on "Information in Infinitary Processes", 3-4 December 2013, Complexity Sciences Center, UC Davis.

Paul Riechers, "Spectral Decomposition", 3 December 2013, Workshop on "Information in Infinitary Processes", 3-4 December 2013, Complexity Sciences Center, UC Davis.

Korana Burke, reviewed Physical Review E "Information Content in Turbulence", 20 November 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

J. P. Crutchfield, "Information in Infinitary Processes", 13 November 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

J. P. Crutchfield, review of "Learning in embodied action-perception loops through exploration", 30 October 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Dowman Varn, "MultiAgent Dynamical Systems", 23 October 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Korana Burke, reviewed Milnor and Thurston's "Kneading Calculus", 25 September and 2 and 9 October 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Chun-Biu Li (Hokkaido) "Single Molecule Spectroscopy and Computational Mechanics", 17 September 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

John Mahoney, "Crypticity in Stochastic Processes: Parts I and II", 4 and 11 September 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Alec Boyd, "Information Engines: Parts I and II", 21 and 28 August 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Brenden Roberts, "Study of Time Reversal in Physical Processes", 14 August 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Meetings
--- Postdoc Korana Burke organized a symposium on computational mechanics at the Annual Meeting of the Society for Industrial and Applied Mathematics, Chicago, Illionis, (July 2014).
--- UCD group (Crutchfield, Boyd, Riechers) weekly visits to Redwood Center for Theoretical Neuroscience, UC Berkeley.
--- Nonequilibrium discussion meeting, every two weeks at the Redwood Center for Theoretical Neuroscience, UC Berkeley. (Crutchfield meeting co-sponsor and co-organizer.) See http://csc.ucdavis.edu/~chaos/share/infoeng/InfoEng/Discussion.html.
--- Crutchfield organizer, CSC Workshop on "Information in Infinitary Processes", 3-4 December 2013, Complexity Sciences Center, UC Davis. See: http://csc.ucdavis.edu/Infinitary_Meeting.html.

Technology Transfer

This project lead to the PI being awarded a ARO-based MURI. The expanded effort greatly broadens the impact of the current project's results in collaborations with other universities and via interactions with ARO and ARL (e.g., in Albuquerque).

Continued development of open source library "Computational Mechanics in Python" (CMPy) that consists of all of the project's constructive mathematical results and methods. Planned release as open source software package slated for Winter 2016.

(Reporting Period: July 2012 – June 2015)

Intrinsic Information Processing and Energy Dissipation in Stochastic Input-Output Dynamical Systems

James P. Crutchfield, Principal Investigator
Complexity Sciences Center, Department of Physics
University of California, Davis, California 95616

Statement of the Problem Studied

Recent theoretical and experimental advances in nonequilibrium thermodynamics provide a new understanding of how "intelligent" control can guide the flow of disorganized thermal energy to useful work energy. However, these approaches have yet to account for the diverse kinds of information that complex nonlinear systems are capable of producing and storing. This is particularly a concern regarding the diversity of differently structured irreversible processes, that play key role in limiting computation. Fortunately, computational mechanics accounts for this diversity, but in autonomous dynamical systems. Thermodynamic cycles that perform useful information processing, in contrast, are nonautonomous systems. To analyze embedded information processing, computational mechanics must be extended to controlled dynamical systems. Additionally, it must be augmented to account for the energetics that support information generation and storage.

The project's goal was to explore the mathematical and theoretical foundations necessary to synthesize the new nonequilibrium thermodynamics and computational mechanics into a single framework. The project successfully reached this goal and, leveraging that success, the research effort continues under the ARO-based MURI "Information Engines" (W911NF-13-1-0390), under the PI's leadership. The framework now provides techniques to analyze and predict the mechanisms by which energy flows support information processing. Using these, we are developing broadly applicable principles of emergent organization and hierarchy in complex physical and biological systems, including new bounds on the minimum required energy dissipation for different kinds of information processing.

Approach
The scientific approaches involved consist of:
1. Nonlinear complex dynamical systems: Gives a detailed and structural view of the state-space mechanisms in nonlinear systems that guide and constrain system behavior.

2. Nonequilibrium statistical physics and thermodynamics: Delineates the kinds of work and work cycles required to overcome irreversible processes.
3. Computational mechanics: Allows for the exact characterization of the intrinsic information processing in complex systems.

Several technical approaches will be used identify relevant structures in nonlinear complex systems—equilibria, limit cycles, invariant submanifolds, ε-machines, and measures of intrinsic computation. The approaches include:

1. Analytical methods to solve in closed-form for the simplest prototype system behaviors and emergent properties.
2. Symbolic computing to extend the range of closed-form analysis to nontrivial complex behaviors.
3. Large-scale simulation using high-performance computing to go beyond their limitations.

Typically, nonlinear systems admit analytical solutions only in special cases. HPC-based simulations allow one to explore physically realistic behaviors outside of analytically approximated regimes.

Relevance to Army

Success in these tasks will enhance a number of Army capabilities, including:

1. Fundamental science of nonequilibrium thermodynamics: This is key to understanding emergent organization in a wide range of mechanical, electronic, chemical, biological, and social processes of interest to the Army.
2. Fundamental science of physical information processing: We are developing methods to analyze the nonlinear dynamical mechanisms that underlie the coupling between energy and information flows in complex physical systems.
3. Minimum energy requirements: By setting new bounds on energy dissipation required for information processing, the results will allow for more accurate estimates of optimal energy efficiencies in a wide range of information processing and control systems of interest to the Army.
4. Design efficiency: Building on these bounds, the results will lead to new design paradigms for large-scale, complex systems of interest to the Army.

Summary of the Most Important Results

The original proposal's research strategy was to synthesize the three scientific areas via the following tasks.

Task A: Energetics Introduce energetics into computational mechanics' informational view of complex systems.

Task B: Input-Output Dynamical Systems Develop a symbolic dynamics appropriate to controlled (input-output) dynamical systems by extending computational mechanics from signal generators (ε-machines) to signal transducers (ε-transducers).

Task C: Efficiency of Thermodynamic Information Processing Cycles Perform detailed computational mechanics informational analysis of the cyclic process by which thermodynamic transformations convert control information to free energy.

Task D: Microdynamics Perform a detailed dynamical systems analysis of the state-space organization of the dynamics underlying this same cyclic process.

Though the original proposal was rather ambitious, we believe that each of the tasks was addressed. We also now know that there is much follow-up research to do. In particular, while Tasks A-C are being pursued via the follow-on "Information Engines" MURI, Task D seems particularly deserving future attention.

The Publications (P#), manuscripts Under Review (UR#), and Manuscript in Preparation (IP#) document the task accomplishments and scientific progress. Their publication data and associated reprints and preprints have been uploaded to https://extranet.aro.army.mil. They are listed again below in the Bibliography to provide references for the narrative summary of the accomplishments.

The main highlights for scientific progress and accomplishments over the project are:
1. *Information control of thermodynamical systems*: The project achieved its most important scientific goal to describe how two processes interact: the mathematical foundations of ε-transducers. In short, we successfully extended the computational mechanics of ε-machines to optimal minimal transducers (P8). This opens up a huge range of applications. For example, we now have the mathematical tools with which to analyze controlled nonlinear dynamical systems—what the original proposal called *input-output dynamical systems*. Another example is that we can exactly identify the informational contributions to the flow of information between two systems (IP3). A third, and perhaps the most concrete application, is to analyzing the informational properties of controlled thermodynamic transformations. We recast Szilard's Engine, a version of Maxwell's Demon, showing that (i) it is a chaotic dynamical system whose degree of instability determines its rate of converting thermal fluctuations to useful work (UR4). We also introduced a broad family of fully analyzable information ratchets that operate as engines, consuming random bits on a tape and using the information to guide converting thermal fluctuations to lift a weight against gravity (UR5).
2. *Exact Complexity*: A new level of analytical precision for all uses of information-theoretic measures of complexity was developed. All known complexity measures for stationary discrete-valued hidden processes and dynamical systems with generating partitions can now be calculated in closed form from their ε-machine, if the latter is finite. This has been critical to progress in a number of applications to calculating correlation functions, power spectral densities, and a wide range of information measures. We adapted and substantially extended the methods of holomorphic functional calculus to give closed-form expressions for all functions of ε-machine transitions matrices. The result is that quantities, previously analytically uncomputable, and those that required exponential computational resources are now given by exact, closed-form expression. In computational complexity terms, what were exponential complexity computations are now constant-time algorithms. This is a major advance in the computational efficiency of analyzing intrinsic computation in complex

systems. It also gives much theoretical insight into the very nature of intrinsic computation. (UR3 and IP2)

3. *Mixed-States as Efficient Representations*: A key part of these advances was our extending the underlying representation, the so-called *mixed states*, beyond simple discrete-alphabet and symbolic-dynamic processes to vector-valued and high-dimensional dynamical systems. One practical consequence is that the computational efficiencies we now enjoy for analyzing the intrinsic computation in low-dimensional systems applies to arbitrarily high-dimensional systems, including spatially extended dynamical systems and dynamical networks. (IP4)

4. *Information Processing in Multi-input, Multi-output Channels*: We introduced a consistent set of measures of redundant, synergistic, and unique information in multi-input, multi-output channels. This gives a systematic way of decomposing shared or mutual information into unique "atomic" components and opens up a way to understand how state-space structures in nonlinear dynamical systems support distinct kinds of information processing. (P4)

5. *Chaos Forgets and Remembers*: This project's most historically surprising result showed how chaotic systems create, destroy, and store information. For over a half century chaotic dynamical systems were characterized by a single "system invariant", the rate at which they generated information, called the *Kolmogorov-Sinai entropy rate*. We showed that this rate consists of two radically distinct kinds of information processing: (i) a component that is created and dissipation and (ii) a component that is created but actively stored by the system. (P2, P3, and P9)

6. The foundational and insightful aspect of these results were acknowledged in a *Nature News and Views commentary* on (P2): P. M. Binder and R. M. Pipes, "How Chaos Forgets and Remembers", Nature **510** (19 June 2014) 343-344.

7. *Intrinsic Computation in Continuous Systems*: Computational mechanics has been successfully extended to processes over continuous-time and continuous-state. Our first results showed how to calculate the information anatomy of continuous-state random walks in nonlinear potentials (P3). The second results showed how to do this for continuous-time memoryful renewal processes—a well known class of processes that is widely used, from statistical mechanics to geophysics and neuroscience (P9). For example, using these results, we analyzed the effect of time coarse-graining on information measures of complexity (IP1). To illustrate those mathematical methods, as an application we analyzed the statistical complexity and other intrinsic computation measures for neural spike trains (P6).

8. *Synchronization*: A key property of controlling nonlinear dynamical systems is how the driven system becomes correlated, or not, to the imposed driving signal. To understand this and frame it information-theoretically, we analyzed in some detail and then provided exact calculational algorithms to determine the amount and kind of information and time required for an observer to synchronize to a structured process. (P1)

9. *Structural Inference*: We developed a complete Bayesian inference method to infer the structure of hidden processes from time series data. This goes substantially beyond statistical parameter estimation methods typical of modern machine learning to estimation and modeling in that it makes minimal assumptions about the model classes. The latter, it should be emphasized, is the key issue when attempting to discover structure and not merely verify a

structural modeling assumption. That is, our methods determine the appropriate *model class* from data directly. (P5)

10. *Nonergodic Processes*: We successfully extended the computational mechanics of ε-machines from describing the structure and intrinsic computation in stationary, ergodic processes to that in nonergodic processes. This opens up a much wider range of applications of computational mechanics to, for example, analyzing structural properties of ergodic decompositions, change-point processes, multi-arm bandit processes, and nonequilibrium steady states. (IP5)

11. *Correlations in Finitary Processes*: We showed how to calculate, exactly and in closed-form, the pairwise correlations for any stochastic processes generated by finite-state hidden Markov models. This extends our previous methods that required unifilarity of the generator to the general, unrestricted case of nonunifilar generators. To give a concrete application and physical meaning to the results we demonstrated how the methods provide new insights into the organization of chaotic one-dimensional crystals; that is, into those that have any degree of disorder. (P7)

12. *Computational Mechanics Foundations*: Several technical papers established critical and oft-assumed properties in computational mechanics. This first showed that the original "equivalence-class" or "history" definition of optimal, minimal unifilar predictors is equivalent to the "generator" definition (UR1). The second showed when it is possible, in working with information measures over semi-infinite pasts and semi-infinite futures, to replace them with ε-machine forward-time and reverse-time causal states. (UR2)

Bibliography

Resulting Journal Publications During Reporting Period
P1. R. G. James, J. R. Mahoney, C. J. Ellison, and J. P. Crutchfield, "Many Roads to Synchrony: Natural Time Scales and Their Algorithms", Physical Review E **89** (2014) 042135.
P2. R. G. James, K. Burke, and J. P. Crutchfield, "Chaos Forgets and Remembers: Measuring Information Creation, Destruction, and Storage", Physics Letters A 37**8** (2014) 2124-2127.
P3. S. Marzen and J. P. Crutchfield, "Information Anatomy of Stochastic Equilibria", Entropy **16** (2014) 4713-4748.
P4. V. Griffith, E. K. P. Chong, R. G. James, C. J. Ellison, J. P. Crutchfield, "Intersection Information based on Common Randomness", Entropy **16** (2014) 1985-2000.
P5. C. C. Strelioff and J. P. Crutchfield, "Bayesian Structural Inference for Hidden Processes", Physical Review E **89** (2014) 042119.
P6. S. Marzen, M. R. DeWeese, and J. P. Crutchfield, "Statistical Complexity of Neural Spike Trains", Computational and Systems Neuroscience (Cosyne), Abstract (2014) 1-2.
P7. P. M. Riechers, D. P. Varn, and J. P. Crutchfield, "Pairwise Correlations in Layered Close-Packed Structures", Acta Crystallographica Section A: Foundations and Advances **71**:4 (2015) 423-443.
P8. N. Barnett and J. P. Crutchfield, "Computational Mechanics of Input-Output Processes: Structured transformations and the ε-transducer", Entropy (2015) to appear.
P9. S. Marzen and J. P. Crutchfield, "Informational and Causal Architecture of Discrete-Time Renewal Processes", Entropy (2015) to appear.

Manuscripts under Review and Technical Reports
UR1. N. F. Travers and J. P. Crutchfield, "Equivalence of History and Generator ε-Machines", Electronic Journal of Probability, resubmitted (2015). arXiv:1111.4500 [math.PR].
UR2. J. P. Crutchfield and C. J. Ellison, "The Past and the Future in the Present", Advances in Complex Systems (2015) submitted. arXiv:1012.0356 [nlin.CD].
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- Virgil Griffith (Neuroscience, CalTech), Ph.D. Fall 2014.
- Richard Watson (Mathematics) completed Ph.D. December 2014.

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- Ryan G. James (Physics) completed Ph.D. August 2013.
- John R. Mahoney (Physics) January 2015-present.
- Dowman P. Varn (Physics) August 2014-present.

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- Paul M. Riechers (Physics) Ph.D. Winter 2016, expected.
- Alec Boyd (Physics) Ph.D. Spring 2016, expected.
- Pooneh Mohammediari (Physics), M.S. Fall 2015, expected.
- Benny Brown (Physics), M.S. Spring 2016, expected.
- Greg Wimsatt (Physics) Ph.D. Spring 2016, expected.

Undergraduate Students Involved During Reporting Period
- Alexandra Nilles (NSF REU undergraduate intern, Physics, 2014).
- Greg Wimsatt (Undergraduate intern, Physics, 2013).
- Kevin Taylor (Undergraduate intern, Physics, 2012-2013).
- Brenden Roberts (NSF REU undergraduate intern, Physics, 2013).

Awards, Honors, and Appointments
- PI Crutchfield awarded two-year accelerated promotion due to research accomplishments supported by this grant.
- PI Crutchfield's publication "Regularities Unseen, Randomness Observed" was selected by American Institute of Physics journal *Chaos—Journal of Nonlinear Science* as one of the top 10 publications in the journal's 25 year history.
- Kevin Taylor, "Extending Reinforcement Learning Methods with a Simple Robot", Undergraduate Senior Thesis (June 2013), awarded Highest Honors by Physics Department.
- PI Crutchfield's publication "Chaos Forgets and Remembers" highlighted in *Nature*: P.-M. Binder and R. M. Pipes, "How chaos forgets and remembers", Nature **510** (June 2015) 343-344.
- PI Crutchfield's publication "Chaotic Crystallography" highlighted in *Nature Materials*: P. Ball, "Beyond the Crystal", Nature Materials **13** (2014) 1003.
- Ryan G. James: Assumed post-doctoral research position in Computer Science Department, University of Colorado, Boulder (September 2013-August 2014).
- Ryan G. James: Assumed post-doctoral research position in Complexity Sciences Center, Physics, University of California, Davis (September 2014-present).
- Nicholas F. Travers: Assumed post-doctoral research position in Mathematics Department, Technion University, Israel (September 2013-August 2015).
- Nicholas F. Travers: Assistant Professor, Mathematics Department, University of Indiana, Bloomington. (September 2015-).
- Korana Burke: UC Davis Chancellor Postdoctoral Fellowship, Complexity Sciences Center, Physics Department (2012-2014).
- John Mahoney, Assumed post-doctoral research position in Complexity Sciences Center, Physics, University of California, Davis (September 2014-August 2017).
- Sarah Marzen (Physics, UCB) UC Berkeley Chancellor's Graduate Fellow (Fall 2013-present).
- Sarah Marzen (Physics, UCB) National Science Foundation Graduate Fellow (Fall 2013-present).

Additional information on programs, students, and faculty of the Complexity Sciences Center is available online: http://csc.ucdavis.edu/.

Talks and Presentations: For those by group members see Presentations section filed at https://extranet.aro.army.mil.
1. Sarah Marzen (UCB) "Computational Mechanics Review", July 2014, Hess Group at Columbia University.
2. Sarah Marzen (UCB) "Predictive Inference in Nonequilibrium Steady States", July 2014, Annual Meeting of the Society of Industrial and Applied Mathematics, Chicago, Illinois.
3. Sarah Marzen (UCB) "Information Theoretic Methods of Time Series Analysis", March 2014, Machine Learning seminar, Computer Science Department, University of Hawaii, Manoa.
4. Sarah Marzen (UCB), "Causal Structure of Neural Spikes Trains", April 2014, Redwood Center for Theoretical Neuroscience, UC Berkeley.

5. Sarah Marzen, "Causal Structure of Neural Spikes Trains", April 2014, Joint Redwood-Ganguli-Theunissen Lab Meeting, UC Berkeley.

6. Sarah Marzen, Mike DeWeese, Jim Crutchfield, "Statistical Complexity of Neural Spike Trains", Poster presentation, March 2014, Computational and Systems Neuroscience (Cosyne 2014), Salt Lake City, Utah.

7. Chris Hillar, Sarah Marzen, Urs Koster, and Killian Kopsal, "Hopfield Networks Efficiently Encode Images", Poster presentation, March 2014, Computational and Systems Neuroscience (Cosyne 2014), Salt Lake City, Utah.

8. Alec Boyd (UCD), "Demon Design" (UCD July 2014, Annual Meeting of the Society of Industrial and Applied Mathematics, Chicago, Illinois.

9. Korana Burke (UCD), "Chaos in Ryberg Atoms", July 2014, Summer School on Nonequilibrium Thermodynamics at the Molecular Scale, Telluride Science Research Center, Telluride, Colorado.

10. Training: JPC taught two graduate courses Winter and Spring 2014 on the physics of information and the physics of computation, respectively.

11. PI Crutchfield gave John von Neumann Complexity and Computation Public Lecture "Demonology: The Curious Role of Intelligence in Physics & Biology", Wisconsin Institutes for Discovery. (6 November 2013.)

12. Nix Barnett, "ε-Transducers: Parts I, II, and III", 27 May and 9 and 16 July 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

13. Alec Boyd and Greg Wimsatt, "Quantum Logic", 23 July 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

14. Alexandra Nilles, "Applying Predicted Information Gain to Physically Embodied Agents", 13 August 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis; 14 August 2014, REU Presentations, Physics, UC Davis.

15. Nick Travers (Technion), "Inversions and Longest Increasing Subsequence for k-Card-Minimum Random Permutations", 20 August 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

16. Aleksander Zujev "Coupled Systems", 25 June 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

17. Benny Brown, review of D. Little and F. Sommer "Learning and exploration in action-perception loops", 21 May and 18 June 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

18. Fritz Sommer (Redwood Ctr, UCB), "Predictive Information Gain for Adaptive Learning", 11 June 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

19. Alec Boyd, review of Mlodinow and Brun, "Relation between the psychological and thermodynamic arrows of time", 14 May 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

20. Amanda Young, "Quantum Spin Chains", 30 April and 7 May 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

21. Sarah Marzen, "Information Anatomy of Continuous Stochastic Processes", 16 April 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

22. Alec Boyd and Paul Riechers, review of G. Crooks' UC Berkeley nonequilibrium discussion group "Holes" presentation, 9 April 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
23. Ryan James (U Colorado, Boulder), "Intersection Information", 2 April 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
24. Alec Boyd, review of Klages et al Ch. 4 "Measuring Out of Equilibrium Fluctuations", 26 February 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
25. Korana Burke and Greg Wimsatt, review of Physical Review Letter "Measurement of Stochastic Entropy Product", 12 March 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
26. Alec Boyd, review's Kawaguchi et al "Fluctuation theorem for hidden entropy production", 19 February 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
27. Katie Amrine (Dept Viticulture and Enology) on "Measuring 'Functional' Information in transfer-RNAs to detect and resolve inconsistencies in deep roots of the Tree of Life", 12 February 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
28. Pooneh Mohammadiara on "Elusive Information", 5 February 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
29. Sarah Marzen on "Structural Complexity of Stochastic Renewal Processes", 29 January 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
30. J. P. Crutchfield led discussion on research job prospects and planning scientific and academic careers, 22 January 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
31. J.P . Crutchfield led debriefing of Information Engine Kickoff Meeting and discussion of alternative experimental platforms, 15 January 2014, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
32. Alec Boyd, review of Klages et al Ch. 1 "Fluctuation Relations", 11 and 18 December 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
33. J. P. Crutchfield, "Information in Infinitary Processes", 3 December 2013, Workshop on "Information in Infinitary Processes", 3-4 December 2013, Complexity Sciences Center, UC Davis.
34. Dave Feldman (College of the Atlantic), "2D Information Theory", 3 December 2013, Workshop on "Information in Infinitary Processes", 3-4 December 2013, Complexity Sciences Center, UC Davis.
35. Chris Ellison (WID, Wisconsin), "Countably Infinite Processes", 3 December 2013, Workshop on "Information in Infinitary Processes", 3-4 December 2013, Complexity Sciences Center, UC Davis.
36. Sarah Marzen (UCB), "Continuous-Time Processes", 3 December 2013, Workshop on "Information in Infinitary Processes", 3-4 December 2013, Complexity Sciences Center, UC Davis.

37. Chris Strelioff, "Inferring Infinite-State Processes", 3 December 2013, Workshop on "Information in Infinitary Processes", 3-4 December 2013, Complexity Sciences Center, UC Davis.
38. Alec Boyd, "Information Engines", 3 December 2013, Workshop on "Information in Infinitary Processes", 3-4 December 2013, Complexity Sciences Center, UC Davis.
39. Paul Riechers, "Spectral Decomposition", 3 December 2013, Workshop on "Information in Infinitary Processes", 3-4 December 2013, Complexity Sciences Center, UC Davis.
40. Korana Burke, reviewed Physical Review E "Information Content in Turbulence", 20 November 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
41. J. P. Crutchfield, "Information in Infinitary Processes", 13 November 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
42. J. P. Crutchfield, review of "Learning in embodied action-perception loops through exploration", 30 October 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
43. Dowman Varn, "MultiAgent Dynamical Systems", 23 October 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
44. Korana Burke, reviewed Milnor and Thurston's "Kneading Calculus", 25 September and 2 and 9 October 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
45. Chun-Biu Li (Hokkaido) "Single Molecule Spectroscopy and Computational Mechanics", 17 September 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
46. John Mahoney, "Crypticity in Stochastic Processes: Parts I and II", 4 and 11 September 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
47. Alec Boyd, "Information Engines: Parts I and II", 21 and 28 August 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.
48. Brenden Roberts, "Study of Time Reversal in Physical Processes", 14 August 2013, Dynamics of Learning Group Seminar, Complexity Sciences Center, UC Davis.

Meetings
1. Postdoc Korana Burke organized a symposium on computational mechanics at the Annual Meeting of the Society for Industrial and Applied Mathematics, Chicago, Illionis, (July 2014).
2. UCD group (Crutchfield, Boyd, Riechers) weekly visits to Redwood Center for Theoretical Neuroscience, UC Berkeley.
3. Nonequilibrium discussion meeting, every two weeks at the Redwood Center for Theoretical Neuroscience, UC Berkeley. (Crutchfield meeting co-sponsor and co-organizer.) See http://csc.ucdavis.edu/~chaos/share/infoeng/InfoEng/Discussion.html.
4. Crutchfield organizer, CSC Workshop on "Information in Infinitary Processes", 3-4 December 2013, Complexity Sciences Center, UC Davis. See: http://csc.ucdavis.edu/Infinitary_Meeting.html.